Linearly Polarized 4x4 Microstrip Patch Antenna Array with corporate feed for X-band applications

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Abstract: **The objective of this paper is to design and study a 16 element planar microstrip rectangular patch antenna array (MSPA) at 10 GHz frequency with corporate feed and linear polarization. Initially, a single rectangular microstrip patch antenna has been designed and then it has been extended to design the 4x4 array which paves the way for usage in various applications in the X-band region like wireless communication, satellite communication, and space applications. The fabrication has been carried out on Rogers RT Duroid 5880 substrate and the antenna parameters like return loss, radiation pattern, directivity, VSWR and realized gain has been simulated and measured. It has been found that a high gain of 19.73db has been achieved with this prototype model.**

Keywords – Antenna Arrays, fabrication, return loss, radiation pattern, directivity, gain

I.INTRODUCTION

In recent years, the advancement in communication systems looks for low cost, minimal weight, and low profile antennas that are capable of maintaining high performance over a wide spectrum of frequencies [1-3]. MSPA structures are becoming complex because of many additional features added to the dielectric material, multilayered dielectric structures, periodic loading of the substrate material to avoid the occurrence of surface waves, aperture coupling of the feed to the antenna, by implementing stacked configuration to attain larger bandwidths which are important factors for arrays [4].

Patch, ground plane, substrate and feeding network are the four main parts of a conventional microstrip patch antenna [5]. Patches could be of any size and shape depending on the frequency and optimization requirements. Here again, the commonly used shapes are the rectangular and circular configurations [5]. Feeding for the arrays can be implemented in any one of the following ways – microstrip line, coaxial probe, aperture coupled and proximity feed line. The simplest feeding method is the microstrip feed line [6].

Ease of incorporation with microwave integrated circuits, the feed lines and to the matching networks are the commendable features of microstrip patch antennas that can also be fabricated simultaneously with the antenna structure. They also have some restrictions like narrow bandwidths, lower gain, and efficiency, large ohmic losses in the feed structure of the array. These can be minimized with the effect of some of these limitations for (e.g.) lower gain and lower power handling can be overcome through an array configuration [7].

There are specific applications where preferred performances can be obtained with a single microstrip patch, on the other hand, characteristics such as high gain, beam scanning or steering capability are achievable only when separate radiators are collectively grouped to form arrays. The individual elements of an array may be spatially dispersed to outline a linear, planar or volume array. A linear array contains elements located at finite distances apart along a straight line. Similarly, a two-dimensional array has components distributed on a plane and a volume array has components that are distributed in three dimensions. Usually, the array type is chosen depending on the intended application. As assigned by IEEE standard the X- band frequency ranges from 8 GHz- 12 GHz and the usage of antennas in this frequency range is for radar and satellite communications for short range tracking, missile guidance, marine and airborne intercepts.

In the recent past, numerous research works have been done with different types of antenna arrays and configurations that could be used for various applications. Ali Mavaddat et el had developed an energy harvester at 35 GHz with a 4x4 antenna array that could efficiently convert RF to dc signal [8 14]. Kuldeep Kumar Singh et el have designed and studied MPA arrays of different configurations at 2.4GHz on a FR4 substrate but did not validate their work experimentally and also the dimensions of the patch are comparatively larger [5] H.Errifi et el have designed MPA arrays of different configurations with series and corporate feed structures at 10GHz while they did not produce the fabrication of their prototype models and experimentally proved their analysis and also the antenna gains are lesser than what has been achieved in this work[9]. Roshini.S.Babu et el have done their work on 4x4 MPA arrays that could be used for GSM applications but they did not again validated their results experimentally [10]. K.Leela Rani et el have designed and simulated 1x4 MPA array at 10 GHz using corporate feed and have achieved a moderately low gain of 7.9412 dB[11]. Similarly, there are many structures that have been developed. In this paper, the 4x4 rectangular patch antenna array with corporate series feed structure has been simulated in High-Frequency Structure Software (HFSS) and then the same has been fabricated and tested to validate the simulation results.

The following section of the paper covers the various feed techniques. Section II discusses the microstrip antenna array design, section III discusses the various antenna parameter results and the measurements done and the last section IV gives the conclusion of this study.

II. MICROSTRIP ANTENNA ARRAY DESIGN

A. Theoretical Modal of a Microstrip Antenna

Theoretical model of a microstrip antenna can be explained as given below. At the resonant frequency significant radiation is produced due to strong fields inside the cavity and strong current at the bottom surface of the patch.

$$\overrightarrow{E_t} = 0 \text{ and } \vec{E} = \widehat{a_z}\, E_z(x,y) \qquad (1)$$

Tangential component of the electric field on the patch and ground plane is zero and the electric field is expressed as given above. Separation h between microstrip patch antenna and the ground plane results in close proximity between them thus $\vec{E}$ has z component.

$$\vec{\Delta}\, X\, \vec{E} = -j\omega\mu\vec{H} \qquad (2)$$

$$\vec{E} = -\frac{1}{j\omega\mu}\,\vec{\Delta}\, X\, \vec{E} = -\frac{1}{j\omega\mu}\,\vec{\Delta} X\left(\widehat{a_z} E_z(x,y)\right) = -\frac{1}{j\omega\mu}\,(-\widehat{a_z}\, X\, \vec{\Delta}\ \ E_z(x,y)) \qquad (3)$$

$$\vec{H}(x,y) = \frac{1}{j\omega\mu}(\widehat{a_z}\, X\, \vec{\Delta} E_z(x,y)) \qquad (4)$$

Using Maxwell's equation $\vec{H}$ is determined as shown above. The mode is TM_z and the magnetic field is purely magnetic as seen from the above equation the vector field $\vec{H}$ has only xy component bound by the patch and the ground plane. For the regions mentioned above, field is independent of the Z-component.

$$\overrightarrow{J_s} \cdot \widehat{a_n} = 0 \qquad (5)$$

$\overrightarrow{J_s}$ is the surface current and on the edges of the patch we have

$$\overrightarrow{J_s} = (-\widehat{a_z}\ X\, \vec{H}\,) \qquad (6)$$

$$\widehat{a_n}\ X\, \vec{H}(x,y) = 0 \qquad (7)$$

$$\widehat{a_n}\, X\, (\widehat{a_z}\, X\, \vec{\Delta}\, E_z(x,y)) = 0 \qquad (8)$$

$$\widehat{a_z}(a_n . \vec{\Delta} E_z(x,y)) = 0 \text{ of } \frac{\partial E_z}{\partial n} = 0 \qquad (9)$$

On the patch the lower surface does not have any electric current component normal to the edges of the patch hence, tangential $\vec{H}$ component does not exist i.e Perfect Magnetic Conductor (PMC) [7].

B. Design Parameter Calculation

In this work we have designed 16 elements 4x4 planar array which are broadly used in communication and radar systems as shown in Fig.1. Each entity of the array element can be positioned along a rectangular grid to form a planar array for enhanced control of bean shape and position in space. Planar arrays of printed radiating elements are probable candidates for low-cost scanning array applications and are liable to be utilized in active integrated phased arrays. Planar arrays can be formed by stacking linear arrays columns with a corporate feed arrangement. Though different feeding techniques have been used in literature we have implemented corporate feed for the arrays as it offers more freedom in controlling the feed of each element i.e. amplitude and phase providing better directivity and radiation efficiency, reducing beam fluctuations compared to series fed array. Despite its performance degradation due to radiation, its ease of construction and lower cost makes it a choice for consideration still [13]. Antenna fabricated using a single substrate board can effectively reduce cost and antenna structure complexity [15]. Because of the finite length and width of the patch, the fields at the patches undergo fringing. Since some of the waves traveling the substrate and some in the air and effective dielectric constant ε_{eff} are introduced to account for the fringing and wave propagation in the line [2].

The effective dielectric constant is obtained by

$$E_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\,{}^{h}\!/_{W}\right]^{-1/2} \qquad (10)$$

Where ε_r is the dielectric constant, h is the height of the substrate and W is the width of the patch.Electrically the patch in the microstrip antenna looks greater than the actual physical dimension due to the effect of fringing. The effective length which is the function of effective dielectric constant and width to height ratio is (W/h) [16,17]

$$\frac{\Delta L}{h} = 0.412\,\frac{(\varepsilon_{reff}+0.3)(W/h+0.264)}{(\varepsilon_{reff}-0.258)(W/h+0.8)} \qquad (11)$$

Since the length of the patch is extended by ΔL on each side the effective length of the patch is

$$L_{eff} = L + \Delta L \qquad (12)$$

The resonant frequency of the microstrip antenna which is the function of the length is

$$f_r = \frac{1}{2L\sqrt{\varepsilon_r}}\,\frac{1}{\sqrt{\varepsilon_0\mu_0}} \qquad (13)$$

and the width of the patch is $W = \frac{1}{2L\sqrt{\mu_0\varepsilon_0}}\left(\frac{2}{\varepsilon_r+1}\right)$ (14)

The designed antenna array has a high gain of 19.7 dB and at the same time, it should be compact to allow space optimization. When the gain increases the dimension of the antenna increases, hence a tradeoff has to be done. The proposed antenna topology has been designed at 10 GHz on a Rogers RT Duroid 5880 substrate of dielectric constant (ε_r)2.2 and loss tangent (δ) 0.0004 and substrate height (h) of 10 mil and the conductor thickness of 17μm.

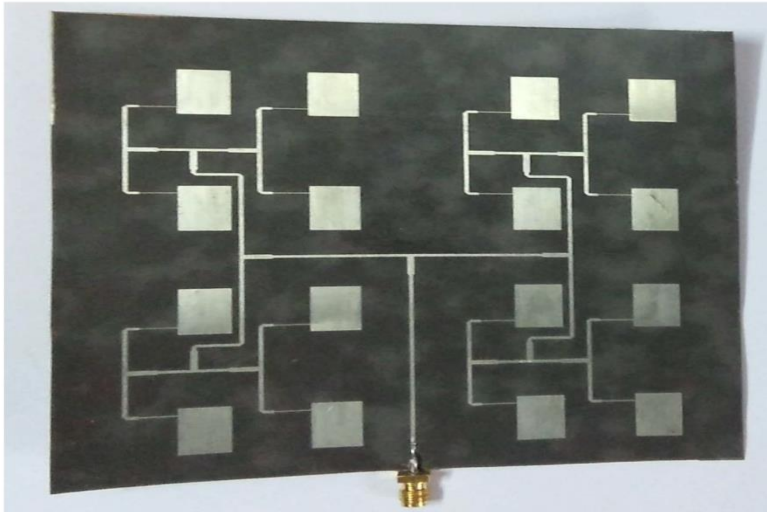

Fig.1. Fabricated 4x4 Microstrip Patch Antenna Array

C. Design Procedure

Firstly the single patch design has to be designed based on the equations which consist of a patch, quarter wave, and feed line. The rectangular patchs length and width are calculated using the equations mentioned. Since a 50Ω surface, mount adapter connector is used to connect the feed line to a coaxial cable, the feed line will be a 50Ω feed line and the feed to the patch goes through a quarter wave transformers.

The length and width of the patch are calculated based on the equation given below:

$$L = 0.49 \frac{\lambda}{\sqrt{\varepsilon_r}} \qquad (15)$$

$$W = \sqrt{\frac{90 \frac{\varepsilon_r^2}{(\varepsilon_r - 1)}}{Z_A}}\ L \qquad (16)$$

$$Z_1 = \sqrt{Z_0 R_{in}} \qquad (17)$$

The above equation is the impedance of the quarter wave transformer. Z_0 is the characteristic impedance of the transmission line and R_{in} is the edge resistance at resonance. This can be extended to the array calculation part for the 50Ω, 70Ω and 100Ω transmission line.

Using the equations (11) to (17) the various antenna configurations were designed and the dimensions are discussed here. The actual dimension of each of the rectangular patch is 13.3mm x 9.7mm. The length and width of the quarter wave transformer is 0.214mm x 5.69mm and the length and width of the 50Ω feed lines is 0.761mm x 5.47mm. The 4x4 array antenna has been fabricated on a ground plane of 136mm x 134mm and the area of the array is 8100nm^2.

III. RESULTS AND DISCUSSION

The prototype model has been fabricated and has been tested to confirm the simulation results.To study the S parameters the fabricated model has been connected to Keysight E5071C ENA Series Vector Network analyzer as shown in Fig .(2) and the radiation pattern analysis has been done in a completely shielded anechoic chamber of size 8x4x4 meters.

Fig.2. 4x4 Microstrip patch antenna Connected to VNA for testing

A. Return Loss

The return loss or the reflection coefficient (S_{11}) is the amount of power reflected from the antenna as a result of inserting a device in the transmission line. Return loss is a ratio in dB relative to the transmitted signal power. The fabricated model connected to the VNA is shown in Fig.2 to study the reflection coefficient parameter. The 4x4 antenna array resonates at 10 GHz at -21.93 dB in the simulation while the same the fabricated model resonates at 10 GHZ with a return loss of -18.77 dB as shown in Fig. (3). The measurements are done using a 50Ω SMA connector soldered at the bottom line of the microstrip line and then connected to the Vector Network Analyzer (VNA). The RF cable affects the performance of the AUT (antenna under test). The slight difference in the reading between the simulation and measured reading could be due to the connector losses and fabrication tolerance.

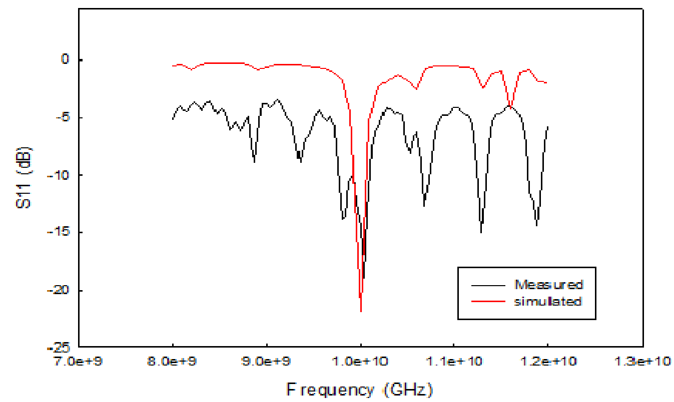

Fig.3. Simulated and measured return loss of the 4x4 Microstrip patch antenna

B. VSWR

To measure numerically how well the antennas impedance is matched to the transmission line is given by the parameter called the VSWR. The Voltage standing wave ratio (VSWR) is a function of the reflection coefficient which describes the power reflected from the antenna. VSWR is a real and positive number, smaller the VSWR better is the matching between the antenna and the transmission line and more power is delivered to the antenna. The VSWR reading for the simulated model is 1.31 whereas for the measured value it shows 1.58 at 10 GHz as seen in the Fig. (4)

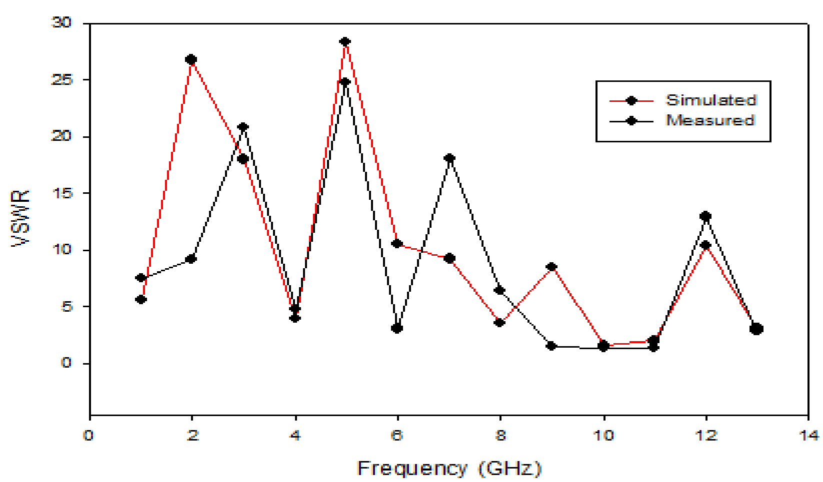

Fig.4. Simulated and measured VSWR of the 4x4 Microstrip patch antenna

C. Radiation Pattern

The far field radiation pattern for the prototype model have been measured in an anechoic chamber which has the facility to measure for the frequency range from 800MHz to 18GHz. Analyzing the radiation pattern helps us to understand the characteristics such as beam width, beam shape, directivity and radiated power. A bandwidth of 140 MHz has been achieved. The radiation pattern along the E-plane and H-plane are shown in Fig. (5) and Fig. (6) and they show a reasonable similarity between the simulated and the measured results. The Co and Cross-polarization of E-field are 19.85 dB and –27.08 dB. Similarly, the Co and Cross-polarization of H-field are 19.85 dB and -22.33 dB respectively. A maximum realized gain of about 19.71 dB has been achieved in the measured readings at 10 GHz as shown in Fig. (7). The HPBW of the E and H planes are $8^0$and 6^0. There are more side lobes compared to all the other designed array structures and the radiation pattern is narrow in nature.

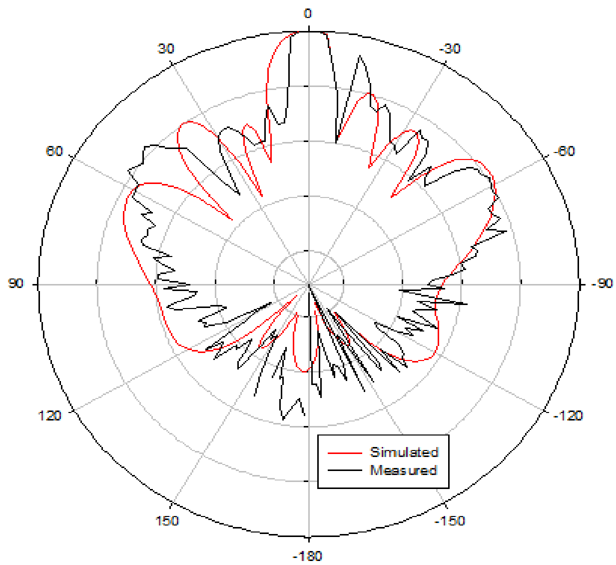

Fig.5. E-plane simulated and measured radiation pattern of 4x4 antenna array

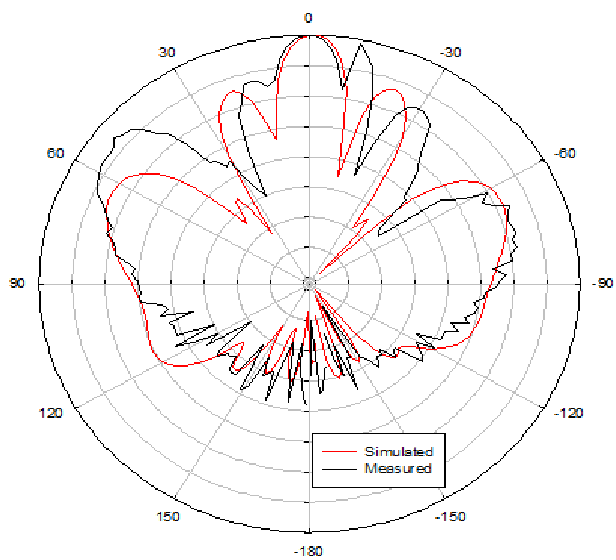

Fig.6. H-plane simulated and measured radiation pattern of 4x4 antenna array

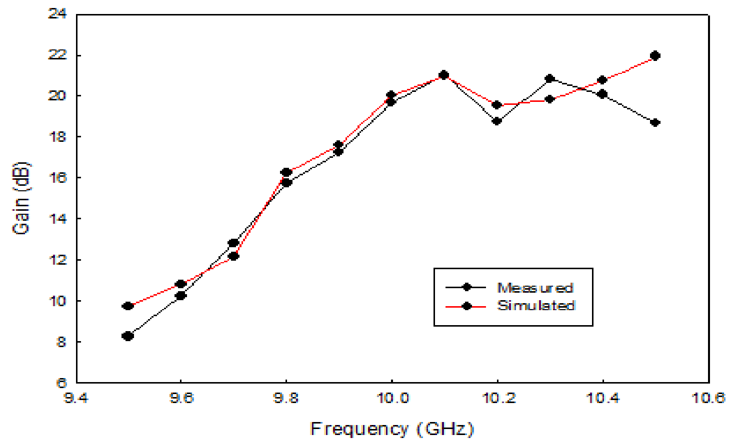

Fig.7. Realized gain of 4x4 patch antenna array

The various antenna parameters are shown in the tabulated form as shown in Table 1.

Table 1. Various antenna parameter values of the 4x4 antenna array

Antenna Parameters		**Values**
Return loss (dB)	Simulated	-21.93
	Measured	-18.77
Bandwidth (MHz)	Simulated	140
	Measured	88
Realized Gain (dB)	Simulated	19.71
	Measured	21.07
VSWR	Simulated	1.31
	Measured	1.25

IV.CONCLUSION

A 4x4 microstrip patch antenna array has been designed with inset corporate feed at 10GHz which could be used for the various X-band applications such as radar and satellite communications. Since the VSWR value is less it indicates that there is a good impedance match. Also, the return loss value is about -21.93 dB. The HPBW of the E-plane and H plane are 8^0 and $6\ ^0$ which indicates that it has narrow beam widths and can be used for high directive applications. But the existence of side lobes has to be reduced so that it can have better performance. The maximum gain of 19.71 dB has been achieved with this model.

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